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EXTENDED ARRAY EVALUATION PROGRAM

Terence W. Harley

Texas Instruments, Incorporated

Prepared for:

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**FINAL REPORT**

**EXTENDED ARRAY EVALUATION PROGRAM**

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## ABSTRACT

Work performed on Contract F33657-72-C-0725 has been reported in detail in a series of seventeen special reports. This final report summarizes the material covered in each of the special reports and discusses the conclusions obtained. The seven tasks in the program included evaluations of the Alaskan Long Period Array, the long-period Norwegian Seismic Array, the short-period Norwegian Seismic Array, and the stations of the Very Long Period Experiment. The remaining tasks included studies of network capabilities and analysis techniques, evaluation of two signal processing algorithms, and study of the considerations necessary to implement and operate a seismic surveillance network.

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## SECTION I

### INTRODUCTION

This final report summarizes work performed under Contract F33657-72-C-0725, Extended Array Evaluation Program, by Texas Instruments Incorporated at the Seismic Data Analysis Center (SDAC) in Alexandria, Virginia. The program consisted of the following seven tasks:

- Continued evaluation of the Alaskan Long Period Array (ALPA)
- Continued evaluation of the Long Period Norwegian Seismic Array (NORSAR)
- Continued evaluation of the Short Period Norwegian Seismic Array
- Continued evaluation of the stations of the Very Long Period Experiment (VLPE)
- Continued investigation of seismic network capabilities and analysis techniques
- Evaluation of the Three Component Adaptive filter and the Fisher detector algorithm
- Detailed definition and analysis of the considerations necessary to implement and operate a seismic surveillance network.

The detailed results obtained for these tasks have been presented in a series of seventeen Special Technical Reports. This final report summarizes those results in Sections II through VII. All reports issued under this contract are listed in Appendix A.

## SECTION II

### ALPA EVALUATION TASK

The ALPA evaluation task results are presented in four reports. Special Report No. 8 summarizes the overall array evaluation effort. Special Report No. 1 compares direct and indirect methods of measuring surface wave detection probabilities. Special Report No. 2 discusses results from a simulated on-line adaptive processor using ALPA data. Special report No. 5 discusses the effectiveness of reference waveform filters at ALPA. Summaries of these reports are presented below.

A. Special Report No. 8: Final Evaluation of the Detection and Discrimination Capability of the Alaskan Long Period Array.

This report presents the results of a continuation of the evaluation of the 19-element Alaskan Long Period Array (ALPA). It extends the analysis reported last year (Heiting, et al, 1972). Emphasis was placed on building a large data base so that detection methods and discrimination parameters of seismic events might be studied on a regional basis. Specific areas of investigation included:

- Noise analysis
- Regionalization of seismic events
- Matched filter performance
- Analysis of S-wave processing for the Kurile Islands - Kamchatka region
- Seismic event detection thresholds

- Behavior of seismic discriminants.

Data from previous years have been included in the data base and, where applicable, were used in the evaluation.

Summarized below are the major results of each of the areas of evaluation:

1. Noise Analysis

- There appears to be a fairly constant background RMS noise level throughout the year at ALPA in the range of 7 - 10  $m\mu$ .
- For the most part, the higher RMS noise levels ( $> 14 m\mu$ ) appear to be due to sudden increases in long-period non-propagating noise superimposed on the background noise level. Only a few of the high RMS noise levels may be due to storm-generated noise.
- The source azimuths of microseismic noise as recorded at ALPA rarely coincide with azimuths to the area of interest.

2. Matched Filter Studies

- There is considerable variation in improvement of signal-plus-noise-to-noise ratio (SNNR) within a given region for both reference waveform and chirp matched filters.
- The standard deviations are so large than mean SNNR improvement values are almost meaningless.
- Chirp matched filters appear to be slightly more effective than reference waveform matched filters.

- Although the use of matched filters does not appreciably affect the 90% detection thresholds, it increases the number of events detected and lowers the 50% detection thresholds.

### 3. S-Wave Processing Results

- The 90% S-wave detection threshold is just below  $m_b = 4.5$  for the Kurile Island - Kamchatka events.
- A higher percentage of summer events (30%) with  $m_b$  below this 90% detection threshold was detected than of winter events (7%).
- For events with  $m_b = 4.5$  or greater, S-wave A/T values are a good discriminant.

### 4. ALPA Surface Wave Detection Capability

- By region, the 90% detection level (with a corresponding low (< 1%) false alarm level) for surface waves occurs at:

Kamchatka	$m_b = 4.1$
Kurile Islands	between $m_b = 4.1$ and $m_b = 4.2$
Central Asia	between $m_b = 4.3$ and $m_b = 4.4$
Caspian Sea	$m_b = 4.5$
Southern Iran	$m_b = 4.3$
Greece-Turkey	$m_b = 4.5$
Eastern Kazakh	$m_b = 5.5$ (Presumed Explosions Only)

- The 90% detection levels for the winter and summer event suites are at  $m_b = 4.5$  for the winter and at  $m_b = 4.4$  for the summer. This difference in detection levels is believed to be due to the slightly higher noise levels of the winter months.

5. Behavior of the Standard Discriminants

- As long as the peak-to-peak amplitude of a surface wave was measured at the highest amplitude, the resulting value of  $M_s$  did not appear to depend upon the period of the waveform at which this amplitude was measured.
- With the exception of one presumed explosion, which may actually have been two explosions, the  $M_s - m_b$  discrimination method achieved complete separation of earthquakes and presumed explosions. The Love wave  $M_s - m_b$  appears to be a better discriminant than the Rayleigh wave  $M_s - m_b$ .
- Using all available earthquake data with  $m_b$  values equal to or greater than the 100% detection level and less than 5.6, the following  $M_s - m_b$  relationships were derived:

for Love wave  $M_s$ :  $M_s = (1.2 \pm 0.2)m_b - (2.1 \pm 1.1)$

for Rayleigh wave  $M_s$ :  $M_s = (1.2 \pm 0.2)m_b - (2.2 \pm 0.9)$

The error estimates for the slope and intercept were measured from the 95% confidence limits of the computed least-mean-square-error fits to the data.

- AL and AR were not as successful in discrimination as  $M_s - m_b$ . With the removal from the data set of the presumed double explosion, separation between the earthquake and presumed explosion populations was complete except for the Kamchatka area AR data. AL data showed better separation than AR data.

With the termination of the three-year evaluation of the detection and discrimination capabilities of ALPA, the following conclusions can be made about its characteristics and performance:

- Signal similarity across the array generally is good. As expected, similarity across the full 19-element array is less than that across the limited 9-element array. The average signal correlation coefficient for the vertical component is 0.84 for the full array and 0.93 for the limited array.
- The beamsteer signal attenuation averages about 2 dB across the full array and about 1 dB for the seven-element hexagonal subarray on all three components.
- The noise field at ALPA is characterized by a fairly constant background RMS noise level of 7 to 10 m $\mu$  (on a single channel) which is punctuated during the winter months by bursts of long-period non-propagating noise. These bursts can temporarily double or triple the RMS noise level and hence decrease detection capability. Propagating storm-generated noise is confined to a narrow band around 18 seconds and variations in this peak do not significantly affect detection capability. The source azimuths of propagating microseismic noise rarely coincide with azimuths to the area of interest. Noise levels are essentially the same on all three components.
- Noise reduction achieved by beamsteering is very close to  $\sqrt{N}$ , hence output beam RMS noise levels usually are between 1.5 and 2.5 m $\mu$ .
- The ALPA noise is not time stationary; substantial variations in wavenumber structure have been observed at the microseismic peak in a two-hour period. Unless the design noise is within a very few hours of the data to which a multichannel filter is to be applied, there is no advantage of a multichannel filter over beamsteering.

- The matched filter studies indicate that, in general, chirp matched filters perform slightly better than reference waveform matched filters in that they yield essentially the same mean SNNR improvements as the reference waveforms but have less variation in improvement among test events. Since matched filters decreased the number of otherwise undetected events by about 20%, thereby lowering the 50% detection levels, they are of value in event detection studies.
- Two-component beamforming as performed in 1971 yielded SNNR gains over the one component beam of only one to two dB in the bandpassed output beam. Therefore, two-component beamforming was considered unsatisfactory as a signal enhancement technique and was not used in the 1972 evaluation.
- The S-wave 90% detection threshold was determined to be at  $m_b = 4.5$  for Kurile Islands - Kamchatka events and at  $m_b = 5.5$  for Central Asian events. The S-wave A/T discriminant is good for events having  $m_b$  values at or above these detection thresholds.
- The surface wave 90% detection levels were determined to be at  $m_b = 4.1$  for Kurile Islands - Kamchatka events, at  $m_b = 4.4 \pm 0.1$  for Eurasian events, and at  $m_b = 5.5$  for Eastern Kazakh presumed explosions. The winter suite 90% detection level was found to be at  $m_b = 4.5$  and the summer 90% detection level at  $m_b = 4.4$ . This difference is believed to be due to the higher RMS noise levels occurring during the winter months. Detection levels for a nine-element subarray are only 0.1 to 0.2 magnitude units above those for the full array.
- The best earthquake-presumed explosion discriminant appears to be the  $M_s - m_b$  relationship. The  $M_s - m_b$  relationship



determined from Love wave energy is a slightly better discriminant than the corresponding relationship determined from Rayleigh wave energy. The  $AL-m_b$  and  $AR-m_b$  discriminants, while inferior to the  $M_s - m_b$  discriminants, are useful in earthquake presumed explosion discrimination studies.  $AL-m_b$  is a better discriminant than  $AR-m_b$ .

- Using only those earthquakes having  $m_b$  values at or above the 100% detection level and below  $m_b = 5.6$ , the following  $M_s - m_b$  relationships were determined:

for Love wave  $M_s$ :  $M_s = (1.2 \pm 0.2)m_b - (2.1 \pm 1.1)$

for Rayleigh wave  $M_s$ :  $M_s = (1.2 \pm 0.2)m_b - (2.2 \pm 0.9)$

The error estimates for the slope and intercept were determined from the 95% confidence limits. These relationships are clearly different than the Gutenberg-Richter relationship  $M_s = 1.59 m_b - 3.97$  and indicate that the  $M_s - m_b$  slope in the  $4.2 \leq m_b \leq 5.6$  range is lower than that at higher magnitudes.

The following areas should be investigated in any future analysis of ALPA:

- The indicated upward trend of the RMS noise level from day 241 to day 361 of 1972 should be investigated to more fully determine if it is different from the corresponding time period of 1971. This would require more noise samples taken in the above mentioned period and an extension of this period into 1973.
- More data for reference waveform matched filters and chirp matched filters should be compiled to make possible a more thorough investigation of their regional characteristics.
- More events from Central Asia should be processed to make possible the subdivision of this region. In particular, the

differences in detection of Western Sinkiang events and Hindu Kush events should be investigated. At present, the small number of events in these areas makes it impossible to do more than note that most events from Western Sinkiang were detected, but few from the Hindu Kush area were detected.

B. Special Report No. 1: Indirect Estimates of Surface Wave Detection Probabilities.

An item of primary interest in the monitoring of underground nuclear tests is the surface wave detectability of a given array or station. In the context of this report detection levels are set sufficiently high so that for every detected signal it is possible to make a reasonable estimate of the surface wave magnitude  $M_s$  from the Rayleigh wave appearing on a vertical component long period seismometer. The results are equally applicable to measurements obtained with a horizontal component seismometer. The most accurate method for estimating detectability is the so-called direct method. This involves processing a large population of events and plotting the percentage of detections as a function of bodywave magnitude  $m_b$ . The accumulation of a statistically meaningful population, in practice, necessitates data collection over an extended period of time.

An indirect method for estimating detectability, which has also been used (Lacoss, 1969 and Harley, 1971), is based on observed noise levels at the array or station in question. This technique is advantageous in that a shorter data collection period is required to provide reliable results. Perhaps more importantly, if one has some information about the noise levels at a proposed array location, this technique allows projection of the performance of the proposed array. This permits evaluation of the cost effectiveness of the proposed array.

Indirect estimates of detection probability are made by inferring incremental surface wave detection probabilities from observed noise levels at an array or station. In the past fixed  $M_s - m_b$  relationships have been used to express the probability as a function of  $m_b$ . It has been observed that the use of this procedure at ALPA and NORSAR leads to estimates of the 90% detection level which are about 0.5  $m_b$  units lower than directly obtained estimates.

The use of a fixed  $M_s - m_b$  conversion overlooks the fact that at any given value of  $m_b$ , a wide range of  $M_s$  values are normally observed. Thus it is necessary to use available information about the statistical nature of the  $M_s - m_b$  relationship to express surface wave detection probabilities as a function of  $m_b$ . When this is done the indirect estimates are found to be in very close agreement with direct estimates. For events from Central Asia and from the Kuriles-Kamchatka area as observed at ALPA, the direct and indirect estimates of the 90% detection level agree within 0.1  $m_b$  units.

The availability of a reliable indirect method is a valuable asset. Noise measurements from 20 or 30 noise samples appear to provide sufficient information to yield reliable indirect estimates. Reliable direct estimates seem to require 100 or more events for a given region. Thus it is possible to obtain indirect estimates for a new or proposed array or station much more economically and faster than in the case of direct estimates. This presupposes that the distribution of  $M_s$  values at a specific  $m_b$  are not strongly dependent on station location so that the 0.4 standard deviation reported here can be validly applied at new locations.

C. Special Report No. 5: Selection of Reference Waveforms for Matched Filter Processing of Long Period Signals From Seismic Events.

Previous studies (Harley, 1971; Heiting, et al, 1972) have shown that when using a long period signal from one seismic event as a reference

waveform for matched filtering other events in a given area, some uncertainties exist about both the criteria of selection of the reference event itself and the selection of that part of the reference event waveform which will yield maximum processing gain. In this study, the effects that various choices of reference waveforms have on matched filter processing are analyzed.

Three major events were chosen from the Sinkiang Province region as reference events. From each reference event signal trace, reference waveforms of eight different lengths were chosen. Each of these twenty-four waveforms was applied as a matched filter to twenty-one test events from the same area and the improvement in signal plus noise to noise ratio of the matched filter over the bandpass filter was measured. The analysis of these gains leads to the following conclusions:

- In most cases, the separation between the reference event and the test event was the most important factor in signal-to-noise ratio improvement. Closer events tended to produce higher gains; however, even for events within a relatively small region it was difficult to judge beforehand the relative gain of several reference event filters.
- The reference waveform length that is optimum for the majority of events contained the entire waveform excluding later multiple arrivals and scattered energy. This length contained essentially all of the energy in the signal processing band. Some events gave higher gains with other length filters but it was difficult to anticipate which events would do so.
- By applying all of the available 24 different reference waveform lengths (3 events, 8 lengths per event) to each test event and picking the one with the best improvement 2 to 10 dB gains relative to bandpass filtering were achieved for 16 out of the 21

test events located over an area of about 900 x 450 km. Four of the five low-gain events were located at least 420 km from the nearest reference event.

- Optimum Sinkiang Province processing yielded up to 8 dB improvement over to-date routine processing of Central Asia events, at the expense of laborious processing.
- No relationship could be established between the matched filter processing gain and either the event magnitude or its signal-to-noise ratio. For two of the three reference events an obvious trend of decreasing gain with increasing distance was observed; for the third reference event a weaker trend was evident.
- Vertical component reference waveform matched filter processing occasionally gave more than 2 dB different gains than radial component processing due to signal or noise differences between the two components.

Summarizing, although significant processing gains are obtained by a limited number of pre-determinable reference event waveforms, maximum signal-to-noise ratio improvement by reference waveform matched filtering can only be obtained by trial and error use of numerous reference waveform filters generated from a number of reference events located throughout the area. Such a technique yields significant processing gains over routine matched filter and bandpass filter processing, but requires either laborious, or highly automated processing. The effects of such processing on false alarm rates and surface wave magnitude measurements were not investigated in this study; however, related experience leads us to believe that these parameters would behave about the same as observed for "standard" matched filter processing.

D. Special Report No. 2: Simulated On-Line Adaptive Processing Results  
Using Alaska Long Period Array Data

The objectives of the adaptive processing task of the Extended Array Evaluation Program were to:

- Determine the problems in the operation of a real-time adaptive signal estimation processor based on the time-domain maximum-likelihood algorithm.
- Perform theoretical studies relating to the convergence of the algorithm and to analyze the output of the adaptive processor in an attempt to upgrade its performance.

This report deals solely with the problems associated with operating the real-time adaptive processor on ALPA data. A modified version of the TI interim ALPA system (Barnard, 1970), was used to implement the adaptive-filtering algorithm. Theoretical studies of the effect of floating means and roundoff error upon filter performance are contained in this report.

The adaptive-filter output  $y(t)$  at time  $t$  is formed by applying a convolution filter to each channel and summing the outputs of all channels:

$$y(t) = \sum_{i=1}^M \sum_{j=-N}^N a_i(j) x_i(t-j)$$

where  $a_i(j)$  is the filter weight for the  $i$ -th channel at a lag of  $j$  sample points,  $x_i(t-j)$  is the value of the channel  $i$  at time  $t-j$ .  $M$  is the number of channels, and  $2N+1$  is the total length of the filter in points. Prior to forming the filter output, each channel is time-shifted to time-align energy arriving from the desired steer direction.

The adaptive filter weights are updated by the following algorithm:

$$a_i^{\text{new}}(j) = a_i^{\text{old}}(j) + \lambda(t) y(t) \left[ \bar{x}(t-j) - x_i(t-j) \right]$$

where

$$\bar{x}(t-j) = \frac{1}{M} \sum_{i=1}^M x_i(t-j)$$

and  $\lambda(t)$  is the convergence parameter at time  $t$ . This update algorithm incorporates the maximum-likelihood constraints.

The convergence parameter  $\lambda(t)$  is calculated by the formula:

$$\lambda(t) = \frac{2K_s}{M(2N+1) \sum_{i=1}^M P_i(t)}$$

where  $K_s$  is an input parameter, and  $P_i(t)$  is a moving power average for the  $i$ -th channel.  $P_i(t)$  is computed by the formula:

$$P_i(t) = (1 - \mu) \left[ \bar{x}(t) - x_i(t) \right]^2 + \mu P_i(t-1) \quad t \geq 1$$

where  $\mu$  is an input parameter.  $P_i(0)$  is zero, and several values of  $P_i(t)$  are computed before the filter is allowed to vary.

A summary of the results of this study is given below.

Floating DC levels in the data channels transmitted from ALPA caused considerable difficulty in implementing an adaptive filtering system until their effect was studied theoretically and effective remedial action taken. Two steps were necessary:

- The data traces were run through a filter having a response exactly equal to zero at DC.

- The adaptive filtering program was examined to uncover DC bias introduced by the computations. Bias compensation was incorporated into the program and intermediate results were rounded instead of truncated whenever possible.

Roundoff error in the adaptive-filter update equation

$$A^{\text{new}} = A^{\text{old}} + \frac{2K_s X^T A^{\text{old}} (\bar{X} - X)}{(\bar{X} - X)^T (\bar{X} - X)}$$

almost became a serious problem in obtaining the results of this report. When the data points were scaled by a factor of 16, however, error in the input channels to the adaptive filter was reduced to the point where the data vector  $X$  and the beamsteer output vector  $\bar{X}$  were almost as accurate as the corresponding vectors computed with floating-point arithmetic. In one noise sample, this scaling procedure increased the noise reduction of adaptive filtering relative to beamsteering from 2 dB to 6 dB at the convergence rate  $K_s = 0.30$ . The 2-dB noise reduction figure for unscaled data is apparently due to sign reversals in the adaptive filter output  $y(t) = X^T A$  (so that the adaptive filter vector  $A$  moves in the wrong direction) and to zero values  $y(t)$  after roundoff (so that the adaptive filter vector does not move at all). With data scaled by 16, errors in the vector  $(\bar{X} - X)$  and the adaptive filter output  $y(t)$  were predominantly digitization errors. The sensor gain doubling at ALPA in the summer of 1972 should permit these errors to be halved. At the most frequently employed convergence rates (near  $K_s = 0.005$ ), the dominant source of error was the error in rounding the updated filter weights (on the right side of the update equation) to the nearest filter-weight count. The mean angle of error in the vector  $(A^{\text{new}} - A^{\text{old}})$  was estimated as  $18^\circ$  for one summer noise sample at the convergence rate  $K_s = 0.005$ . This angle could have been reduced to  $10^\circ$  if errors in the maximum-likelihood constraint conditions had been corrected



differently. As the convergence rate drops below 0.5%, the filter-weight roundoff error becomes progressively worse until ultimately the filter vector A cannot change. The way to improve this situation is to represent the filter weight more precisely by using a longer computer word. Such a solution would have meant abandoning the special convolution-filter microcode instruction incorporated in the IBM 360/40 computers at SDAC, where a 16-bit filter-weight representation is required. Had filter-weight roundoff error been eliminated, the effect would have been to reduce (probably only slightly) the convergence rate at which the highest adaptive-filtering signal-to-noise gains relative to beamsteering were achieved.

In determining adaptive-filtering signal-to-noise gains, the critical area of concern is the processing improvement for weak signals in the borderline detection range, where the signal-to-noise ratio on the beamsteer output is between 6 and 12 dB. With such weak signals, detection procedures cannot consistently recognize the presence of a signal, and no filter-freeze procedure can be implemented. One signal approximately 6 dB above the noise level on the beamsteer output was used for the critical results. Signal-to-noise gain was measured as the difference between adaptive-filtering noise reduction and signal degradation. Optimum gain was realized near a 0.5% convergence rate. Using noise data from day 238 of 1970, signal-to-noise gain for the weak signal was 1.23 dB broadband, 1.34 dB in the frequency band for periods between 43 and 15 seconds. With noise data from day 203 of 1971, broadband gain was 2.03 dB, narrowband gain 2.19 dB. Due to greater degradation of stronger signals, the signal-to-noise gain was lower for signals 18 to 24 dB above the noise level on the beamsteer output when the adaptive filter set was permitted to update.

With signals as strong as these, it is easy to detect their presence. A scaled version of the Fisher detection algorithm was used for this purpose. With the particular adaptive algorithm employed, the standard

procedure is to freeze the adaptive filter set. When the filter set was prevented from updating upon signal detection, signal degradation was less than 0.1 dB for a signal 18 dB above the noise level on the beamsteer output and almost exact, 0 dB for a signal with a beamsteer-output signal-to-noise ratio of 24 dB. These figures are contrasted with a signal degradation of 0.41 dB for the 6-dB signal at a convergence rate of 0.5%. Although the signal degradation is lower for the two strong signals when the filter is frozen, noise reduction begins to drop as the elapsed time from the point of the filter freeze increases. Loss in noise reduction was measured by twice processing a noise sample from day 232 of 1970. In both cases, the filter was permitted to adapt for the first three hours of the noise sample. In the first computer run, it was allowed to adapt for one more hour. In the second run, it was frozen during the final hour. The apparent trend of the loss in noise reduction indicates that higher signal-to-noise gain is preserved for at least 15 minutes by freezing the filter rather than updating it in the case of the 18-dB signal. Superior gain is maintained much longer for the 24-dB signal.

The alternate adaptive algorithm

$$A^{new} = A^{old} + \frac{2K_s X^T A^{old} (\bar{X} - X)}{X^T X}$$

adapts much less rapidly in the presence of a signal. It is very possible that this algorithm could operate at convergence rates higher than the value  $K_s = 0.005$  without degrading signals any more than the implemented algorithm does at its optimum rate of  $K_s = 0.005$ . If so, greater signal-to-noise gains could be realized through increased noise reduction at higher convergence rates.

One data sample from 2000 to 2357 on day 276 of 1971 was especially rich in signals (both on-azimuth and off-azimuth). The following conclusions can be drawn from this four-hour data sample:

- Off-azimuth events are strongly suppressed in the adaptive-filter beam when the filter set is not frozen. Some off-azimuth signals are virtually annihilated. The more powerful the off-azimuth event, the more it is stifled.
- Greater directional resolution at ALPA and other similar long-period arrays is achievable through the beam-narrowing capability of multichannel filtering. This fact is extremely important if long-period arrays of this type are to be used for signal detection and location or for separation of multiple events. With time-varying adaptive filters, off-azimuth events can be nulled out in proportion to their signal-to-noise ratio with possible complications if two events overlap in time. With fixed non-varying multichannel filters, superdirectivity can be preserved in all circumstances, but then the ability to quell specific bursts of off-azimuth energy in an on-line processing mode is impaired.

Four four-hour noise samples were processed for this report. Adaptive filter beams were steered toward four different look directions in processing two of these noise samples. In eight out of ten cases, the broadband signal-to-noise gain which would have achieved for the weak 6-dB signal was within the range 0.98 to 2.02 dB. In one case, it would have been 0.75 dB; in another, it would have been 2.7 dB. Over the band 0.0234 to 0.0664 Hz (corresponding to periods between 43 and 15 seconds), the signal-to-noise gain for the weak signal would have been between 0.98 and 2.0 dB in six cases, between 2.0 dB and 2.2 dB in three cases. The last case would have yielded a narrowband gain of 3.74 dB. The narrowband values are meaningful if a bandpass filter for periods between 40 and 15 seconds is applied to the data.

### SECTION III

#### NORSAR LONG PERIOD ARRAY EVALUATION TASK

The results of the evaluation of the long period NORSAR array are presented in two reports. Special Report No. 7 covers the evaluation effort from April 1972 to March 1973. Special Report No. 12 covers the evaluation results during the following six months to October 1973. In addition, Report No. 12 discusses the major conclusions of the two and one-half year evaluation of NORSAR. Summaries of these reports are presented below.

A. Special Report No. 7: Continued Evaluation of the Norwegian Long Period Array.

This report presents the results of the evaluation of the Norwegian Long Period Seismic Array (NORSAR) made during the period from April 1972 through March 1973. This work is a continuation of an analysis of NORSAR reported on earlier (Eyres, et al, 1972). The evaluation was directed toward two major goals: the determination of the detection and discrimination capabilities of NORSAR and the investigation of methods which sustain or enhance those capabilities. Five separate studies were made:

- Noise analysis
- Array processing effectiveness
- Matched filter performance
- Signal detection threshold estimation
- Behavior of standard discriminants.

The major conclusions from these five studies of the NORSAR evaluation are summarized below. These conclusions are based on the overall results obtained during the past two years.

1. Noise Analysis

- The ambient noise at NORSAR is strongly seasonal with summertime levels of 5-10 m $\mu$  RMS (20-40 seconds) and wintertime levels of 8-15 m $\mu$ . The noise appears to be almost entirely made up of propagating surface wave energy.
- During the winter, noise levels often rise to levels greater than 25 m $\mu$  RMS. These increased levels are definitely caused by storms in the North Atlantic Ocean, however, the noise generation mechanism is not understood. The duration of these high levels may be between 12 to 36 hours.
- The source directions of the ambient noise are also seasonally dependent and seem to have a few preferred azimuths. In the winter, noise is primarily from the north and west. In the summer, the primary noise azimuth is east. "Summer" noise can be differentiated from "winter" noise by the change in noise azimuth from west to east and vice versa. The direction changes are not strongly correlated with noise levels.

2. Array Processing Performance

These conclusions are based on results from eleven winter noise samples.

- Within the MCF design gate, the MCF processor achieved 2 to 8 dB more reduction in noise than the BS processor in the signal processing band of 0.025-0.059 Hz. Outside of the design gate, this advantage dropped slightly to 0 to 6 dB. Best MCF gains were not obtained when noise levels were highest.

- Array gains of both the MCF and BS processors were seriously degraded when array beam look directions were close to the predominant noise azimuths. For look directions significantly different from the noise directions, the array gains improved and the MCF obtained 2-5 dB additional gain over the BS for on-design noise and 0-4 dB for off-design noise.
  - The MCF typically achieved 3 dB more signal-to-noise ratio improvement than the BS processor in actual signal extraction. This suggests that an MCF processor could lower the NORSAR detection threshold in winter by 0.15  $M_s$  units.
  - In a comparison of MCF and BS processors using the full array and a smaller subarray configuration, the MCF over BS array gain improvements were slightly larger for the subarray.
3. Matched Filtering Performance
- A matched filter parameter was highly successful as the basis for defining seismic regions in Eurasia. The chirp filter length giving optimum signal-to-noise ratio improvement was found to show regular and consistent variations for various regions. Maps were produced showing contours of equal chirp length.
  - Average chirp filter SNNR gains for different regions ranged from 0.7 to 4.8 dB with typical gains of 2 dB. The variation in gain within a region was rather large. The standard deviation of gain for the regions ranged from 0.5 to 2 times the average gain with usual values of 0.6 of the gain.
  - Chirp filters produce a small increase in the number of detected events. The  $m_b$ 's of these events were in the neighborhood of the 50% detection level. These additional detections did not significantly affect the 90% detection threshold.

- The SNNR gain of reference waveform filters was shown to be degraded in the presence of signal-like energy in the background noise. This implies that a RWF may not be effective in separating a desired event from an interfering event. Chirp filters are less adversely affected.
4. NORSAR Surface Wave Detection Capability
- All detections were measured with a false alarm level of less than one percent. The 90 percent detection thresholds, by region, are the following:
    - All events combined:  $m_b = 4.5$
    - Kurile, Kamchatka, Okhotsk:  $m_b = 4.6$
    - Central Asia:  $m_b = 4.5$
    - Eastern Kazakh (presumed explosions only):  $m_b = 5.1$ .
  - The 90 percent detection threshold at NORSAR shows a strong seasonal dependence. This may be attributed to the increased ambient noise level during the winter. The winter threshold is at  $m_b = 4.5$ . The summer threshold is at  $m_b = 4.2$ .
  - Chirp matched filters are probably not very effective in lowering the 90 percent detection threshold.
5. Behavior of Standard Surface Wave Discriminants
- Reasonably good separation was obtained by the  $M_s - m_b$  discriminant. Overlap of event classes was found for eight events, however, none were overlapped on both Rayleigh and Love wave  $M_s$ . There was essentially no difference in separation between Rayleigh  $M_s - m_b$  and Love  $M_s - m_b$ .
  - AR and AL appear to be better discriminants than  $M_s$  at NORSAR. Good separation was obtained for both AR and AL.

With the exception of one presumed explosion (actually two events with origin times eight seconds apart), minimum separation by AL was by a factor of four.

B. Special Report No. 12: Final Evaluation of the Norwegian Long Period Array.

This report presents the cumulative and final results of a study of the Long Period Norwegian Seismic Array (NORSAR). The study began in April 1971 for the purpose of evaluating:

- The array detection capability for Eurasian events
- The performance of various discriminants at NORSAR for Eurasian events
- Methods of sustaining or enhancing these capabilities.

These three objectives were achieved by the following studies:

- Noise analysis
- Signal analysis
- Array processing effectiveness
- Matched filtering performance
- Detection threshold estimation
- Behavior of standard discriminants.

The major conclusions from the six studies of the NORSAR Long Period Array Evaluation are summarized below. These conclusions are based on all the results obtained during the past two and one-half years.



1. Noise Analysis

- The noise level in the 20-40 second band is strongly seasonal. Summer levels (March to October) are around 7 m $\mu$  RMS and fairly constant. Winter noise is more erratic with levels varying from 8 to 15 m $\mu$  RMS. The maximum observed level was 79 m $\mu$  RMS.
- The high winter noise levels are caused by storms in the North Atlantic Ocean and many last from 12 to 36 hours. The noise generating mechanism is not understood.
- Noise directions are also seasonally dependent at NORSAR but are not strongly correlated with noise level. Winter noise tends to be strongly directional with preferred azimuths of 0 $^{\circ}$ , 250 $^{\circ}$ , and 280 $^{\circ}$ . Winter noise coherence is high at the frequencies of peak power. Summer noise is generally isotropic often with weak easterly direction and has low coherence particularly in the signal processing band of 17 to 40 seconds.

2. Signal Analysis

- Based on energy spectra, uncorrected for instrument response, the majority of the signal energy generally lies between periods of 17 to 40 seconds. Some Central Asian events, however, contain significant energy down to 13 seconds.
- The arrival azimuth of the signal is along the great circle path with only small deviations. Some events have shown shifts in arrival azimuth deep in the coda and at the higher frequencies.
- Signal similarity usually is very high along the propagation direction but degrades rapidly normal to the propagation path.

### 3. Array Processing Performance

#### a. Full Array

- Multichannel filter improvements in array gain are seasonally dependent for off-design noise in the signal band (0.025-0.059 Hz). The MCF averaged 4.0 dB more array gain than the beamsteer in winter noise conditions. This implies that the use of an MCF in winter could lower the detection threshold by 0.2  $M_s$  units. Little gain improvement was obtained in the summer.
- Signal amplitude degradation of the beamsteer processor is 2.0 dB for the Rayleigh wave and 2.2 dB for the Love wave. The MCF signal degradation is slightly greater than the beamsteer for the samples used.

#### b. Reduced Array

- The high signal similarity over the reduced array significantly increased the performance of both the MCF and beamsteer processors. For the 22 noise samples investigated, the MCF averaged 4 dB more noise suppression than the beamsteer processor.
- In contrast to the full array, the MCF improvement over the beamsteer is strongly correlated with the beamsteer noise level. The MCF improvement over the beamsteer for the reduced array is slightly less seasonally dependent than is the full array.
- The signal amplitude degradation for the beamsteer is 1.4 dB for the Rayleigh wave and 1.6 dB for the Love wave. These values are 0.6 dB less than for the full array. MCF signal loss is slightly more than the beamsteering loss.

c. MCF Processing Using One Noise Sample for MCF Design

- Using a single sample of summer noise for MCF design, array gain improvement of the MCF, when applied to events up to 15 days from that sample, showed no correlation with time separation.

4. Matched Filtering Performance

- Considerable effort was expended to determine the signal processing band. The 17-40 second period band (0.025-0.059 Hz) seemed to show slightly better overall performance than the other bands investigated and was adopted as the routine signal processing band for NORSAR.
- Chirp filter lengths were successfully used to regionalize the events. Chirp filters giving optimum SNNR improvements were found to have lengths which vary in a regular, consistent fashion over the Eurasian continent allowing contour maps of equal chirp length to be made.
- The SNNR improvements of the chirp filter averaged 2 dB more than the equivalent bandpass filter. For a given region, the standard deviations of the gains were typically 0.6 times the mean gain.
- Reference waveform filters (RWF) were not used on a routine basis at NORSAR. The marginally superior performance of the RWF did not seem worthwhile because chirp filters offered more stable and uniform results, were less sensitive to the presence of signal-like noise, and parametric values were simple to generate and determine.

- Chirp filters produced a small increase in the number of detected events at the 50 percent detection threshold level but did not materially affect the 90 percent detection threshold level.
5. Detection Threshold Estimation
- The estimated 90 percent detection threshold (with a false alarm rate estimated at less than 1 percent) for the various event populations are:
    - All Eurasian earthquakes  $m_b = 4.5$
    - Central Asia  $m_b = 4.6$
    - Presumed Explosion  $m_b = 5.1$  (this value is based on a few events and may be unreliable)
    - Kurile-Kamchatka areas  $m_b = 4.5$
    - Summer events  $m_b = 4.3$
    - Winter events  $m_b = 4.5$ .
  - The difference between the summer and winter 90 percent detection threshold is attributed to the increased noise level at NORSAR during the winter months.
6. Behavior of Standard Discriminants
- The  $M_s - m_b$  criteria achieved complete separation between event classes for both Rayleigh and Love waves.
  - AL and AR also achieved complete separation between classes and appear to give slightly better separation of classes than  $M_s - m_b$  at NORSAR. At ALPA the AL, AR versus  $m_b$  criteria performed more poorly than the  $M_s - m_b$  criterion.

The results from the NORSAR evaluation conducted during the past two and one-half years have pointed out areas which should be studied in any future analysis of NORSAR.

- The correlation of ambient noise level with the presence of winter storms in the North Atlantic ocean suggests two areas of investigation. First, the noise generation mechanism should be identified as either a coastal surf action, an interaction of deep water waves with continental shelves, or an open ocean mechanism. This would require fairly comprehensive wave and weather information from both Norway and England and possibly seismic data from English stations. Second, multichannel filters should be used on wintertime data. These may be fixed or possibly time-adaptive. If the first study demonstrates a structural effect, fixed MCF's may be useful for processing of winter data.
- More events from central Asia should be analyzed. Some areas show unusual behavior in both spectral content and dispersion, particularly around the Caspian Sea, Tadzhik, and Kirgiz. These events tend to have particularly large high-frequency energy content, relatively wide dispersion, compared to Sinkiang, China, and more northerly areas, and occasionally reverse dispersion. It may be desirable to use wider processing bandwidths for central Asian events.
- Chirp matched filters should be evolved to more sophisticated non-linear models while maintaining simplicity. This may realize significantly higher signal-to-noise ratio gains for the central Asian events in particular.
- Maps of chirp filter length were successful in indicating seismic region boundaries. There is some evidence that the boundaries of the tectonic systems of Asia can be correlated with these maps. It may be possible that such maps, computed for several seismic stations, may be helpful in pointing out geologically interesting areas.

## SECTION IV

### NORSAR SHORT PERIOD ARRAY EVALUATION TASK

The evaluation of the short period array at NORSAR is also discussed in two reports. Special Report No. 9 covers the work from April 1972 to March 1973 and Special Report No. 11 covers the work in the succeeding six months to October 1973, when the evaluation was finished. The discrimination capability of the combined long period and short period arrays at NORSAR is discussed in Special Report No. 13. A summary of the results of these three reports is presented below.

#### A. Special Report No. 9: Continued Evaluation of the Norwegian Short-Period Array.

This report presents the results of an ongoing evaluation of the short-period (SP) Norwegian Seismic Array (NORSAR), using seismic data recorded during 1971 and 1972. The overall objectives of the NORSAR SP evaluation were:

- Determine the best processing methods for enhancing the signal-to-noise ratio of Eurasian events
- Determine the array capability for Eurasian events
- Evaluate the performance of short period discriminants at NORSAR
- In conjunction with long period NORSAR data, determine the detection and discrimination capability of NORSAR for Eurasian events.

Substantial progress was made toward achieving the first three objectives. However, the results presented in this report may still be improved as the data base for the evaluation is expanded. Work toward meeting the fourth objective was still at an initial stage, and will be given more attention in a subsequent report.

Five analysis tasks were undertaken in order to meet the first three objectives stated above:

- Noise analysis
- Signal analysis
- Array processing effectiveness
- Detection threshold estimation
- Behavior of SP discriminants.

Results from noise analysis were presented last year in Special Report No. 6 (Barnard and Whitelaw, 1972) under the Extended Array Evaluation program. No additional noise analysis has been undertaken this year.

The events on which the results from the remaining tasks are based were located primarily on the Eurasian continent. A total of 344 events have been analyzed, including 106 events which were discussed in the report on this work last year (Barnard and Whitelaw, 1972). The results from the latter events are included in the total data base.

Geographically, the events are concentrated principally in the northwestern Pacific (from Kamchatka to Taiwan) and in south central Asia (north and west of the Himalayan system). Thirty-nine events from the Mediterranean region are included as well as eight from the Arctic Ocean

and eight from continental North America. Twenty-one events are presumed explosions; including eight from eastern Kazakh, one from western Kazakh two from the Ural Mountains, three from western Russia, one from Novaya Zemlya, one from the Aleutian Islands and five from Nevada.

Conclusions about the performance of the short period NORSAR array, based on analysis of 344 signals (primarily from Eurasia) are given below.

Data quality was excellent. For about one-half of the samples all 132 sensors were operational. The worst data loss encountered was 24 sensors. For six events spikes were found in the data, but these events could still be processed. Phase reversals were observed for a few seismometers during parts of 1971, but this problem had been corrected for 1972 data.

Major conclusions from the signal analysis are:

- Amplitude variations across the subarrays are generally large (typically 4:1) and show strong dependence upon source region. However, within narrow regions a high degree of consistency is seen, and it appears that most of the amplitude variations may be explained by scattering effects due to the irregular structure of the Mohorovicic discontinuity (Moho) underneath the NORSAR array.
- Time delay anomalies (deviation from plane wave propagation along the great circle path) are significant between subarrays, but a consistent set of anomalies can in general be obtained for events of epicentral distance greater than 30 degrees from NORSAR. Part of the observed anomalies, but not all, can be explained from the variations in depth of the Moho below NORSAR.



- For certain close-in events, notably events from Italy, low and high frequency signal energy appear to follow different paths; the 0.5 Hz energy arriving at NORSAR 1-2 seconds before the 1 Hz energy. Significant differences were found in this case between time delay anomalies for the low and high frequency signal bands.
- Considerable variation in regional signal characteristics is observed. Signal waveform complexity shows the expected decrease with increasing distance, except for some high complexity events from Taiwan and south Kamchatka. Signal spectral content is more unpredictable, with low frequency signals being observed mainly from Italy, Turkey, Kirgiz, and Taiwan while Greece, Tadzhik, and Kurile Island events generally produce high frequency signals.
- Significant spread is observed between LASA/ PDE and NORSAR magnitudes (as measured by the TI analyst). NORSAR magnitudes are generally lower, with an average negative bias of 0.2 - 0.3  $m_b$  units, and with a standard deviation of 0.3 around this bias.

The following conclusions were derived concerning array processing performance:

- Average wide band subarray beam-to-array beam SNR improvement is 10 dB, with 80 percent of all examined events having values between 9 and 12 dB. As expected, array gain is considerably lower for close-in events and presumed explosions with high dominant frequency.
- Average wide band signal degradation from subarray to array level is 3 dB. Together with the 10 dB SNR improvement, this

is consistent with the expected 13.4 dB noise reduction for a 22-element array.

- Diversity stack array beamforming yields an average improvement over the adjusted-delay array beam of 1.0 dB for unfiltered and 1.6 dB for filtered signals (standard filter).
- Compensating for time delay anomalies on the subarray level yields an average of only 0.5 dB SNR improvement for three close-in events compared with plane wave subarray beams. Thus plane wave delays appear to be adequate on the subarray level.
- SNR improvement achieved with the standard filter averages 7 dB, with values for individual events ranging from -4 to 16 dB. Significant regional dependence is seen in these numbers. Filter signal suppression averages around 6 dB, and also shows a large variability between events.

Our conclusions concerning NORSAR detectability are:

- 90% incremental detection threshold is close to 4.2 for all of Eurasia combined, and slightly higher (4.3) for the Japan to Kamchatka arc.
- The number of events reported in the NORSAR seismic bulletin for January-March 1972 appears to be considerably lower than would be expected from our analysis of NORSAR detectability. Presumably, this is due partly to conservative prethreshold for operation of the NORSAR Event Processor, partly to the inherent limitations of the automatic signal detector.
- A theoretical model based on NORSAR seismic noise level and processing losses seems to give detectability estimates which are consistent with our experimental results.

Conclusions with respect to short period discrimination are:

- Discriminants based on spectral energy distribution seem to be superior to discriminants based on the complexity of the signal waveform.
- No single discriminant is able to separate completely between presumed explosions and earthquakes. The best separation is obtained by considering the spectral ratio of energy in the bands 1.5 to 5.0 Hz and 0 - 0.55 Hz, although reservations must be taken due to possible bias caused by the high signal-to-noise ratios for all events in the presumed explosion population.
- It appears possible to improve separation significantly by considering a combination of discriminants. However, no formal multivariate model was established to determine an optimum criterion.
- A preliminary study of the performance of short period discriminants versus that of  $M_s - m_b$  and other SP-LP discriminants gave the expected result that the latter ones in general produce a better separation between earthquakes and presumed explosions.

B. Special Report No. 11: Final Evaluation of the Norwegian Short Period Array.

This report presents the results of the final phase of the evaluation of the short period Norwegian Seismic Array (NORSAR). It extends the analysis reported last year (Barnard and Whitelaw, 1972) and Special Report No. 9 discussed in section A above. The overall objectives of the NORSAR SP evaluation were:

- Determine the best processing methods for enhancing the signal-to-noise ratio of Eurasian events
- Determine the array detection capability for Eurasian events
- Evaluate the performance of short period discriminants at NORSAR
- In conjunction with long period NORSAR data, determine the detection and discrimination capability of NORSAR for Eurasian events.

The fourth objective stated above is the topic of Special Report No. 13 and will be discussed in the next section. Five analysis tasks were undertaken in order to meet the first three objectives:

- Noise analysis
- Signal analysis
- Evaluation of array processing effectiveness
- Detection threshold estimation
- Analysis of the behavior of SP discriminants.

The results presented in this report are based on seismic events and presumed explosions from 1971 and 1972. A total of 567 events have been processed; all but 15 of these were from Eurasia. The number of presumed explosions totals 33 from Eurasia and 6 from the Western Hemisphere. The complete data base for the NORSAR SP evaluation includes the 344 events analyzed in Special Report No. 9 as well as an additional 223 events, mostly from June and July of 1972, which have been processed since then.

Throughout 1971 and 1972, the quality of the NORSAR SP data was excellent. For a total of 25 of the events selected by TI, no data was

available from NORSAR. This corresponds to less than five percent of our data requests, and thus indicates that the array was operational for an average of more than 95 percent of the time. For about one-third of the processed events all 132 sensors were operational. In most other cases one or two subarrays were dead or contained calibration signals; the worst data loss was 33 sensors. Data spikes were observed for ten events, but in each case only one or very few sensors were affected; consequently these events could still be satisfactorily processed.

The results of the two and one-half year NORSAR short period evaluation program are summarized below:

1. Data Quality

The SP data recorded at NORSAR has been of consistently high quality throughout the evaluation period, which spanned the time interval from March 1971 through December 1972. On the basis of more than 500 events and 70 noise samples processed by TI for this period, the following observations were made:

- Data was available from NORSAR for more than 95 percent of the time intervals requested by TI
- In most cases at least 20 subarrays were operational. The worst data loss for a single event was 33 out of 132 sensors
- Data spikes were observed for 10 events, but these events could still be processed
- Phase reversals affected 8 sensors during parts of 1971, but was not observed on 1972 data
- The SP seismometers appeared to be well equalized across the NORSAR array.

## 2. Noise Analysis

The following conclusions concerning noise analysis are based on 72 sample intervals:

- The noise spectral shape is very simple, with a peak at about 3 to 6 seconds and a rapid fall-off toward short periods. The spectral shape does not change significantly across the array.
- Noise levels are very similar across the array. Maximum single sensor variations typically are  $\pm 6$  dB, and most sensors are within  $\pm 3$  dB of the average single sensor level. Variation among subarray beam noise levels is  $\pm 2$  dB.
- Wideband RMS noise level shows a significant variation with time, and correlates strongly with storm activity in the North Atlantic Ocean. The spectral peak generally shifts towards lower frequencies as the noise level increases. Wintertime wideband noise levels are on the average 6 dB higher than the summertime levels; this difference is less evident when the "standard" bandpass filter is applied.
- Typical RMS noise levels are:  $0.5 \text{ m}\mu \pm 6$  dB for the wideband array beam.  $0.12 \text{ m}\mu \pm 3$  dB for the array beam through the standard filter. This last number is about a factor of 2 higher than the detection band noise level for LASA.
- Multiple coherence levels within a subarray are low except at the 3 to 6 seconds microseismic peak. Inter-subarray multiple coherencies are low over the entire 0 to 5.0 Hz band.

## 3. Signal Analysis

Our conclusions from the signal analysis are based upon the processing of 567 events; and can be summarized as follows:

- Except for a few close-in, high frequency events signal similarity is good within a subarray. Among subarrays, however, similarity is quite variable.
- Amplitude variations across the array are large, typically 4:1, while variations as high as 10:1 have been observed for Kazakh events. The amplitude patterns are strongly dependent upon source location, but consistent behavior is generally seen within narrow regions. It appears that most of the amplitude variations may be explained by scattering effects due to the irregular structure of the Mohorovicic discontinuity underneath the NORSAR array.
- Time delay anomalies (deviation from plane wave propagation along the great circle path) are not significant for subarray beamforming. Anomalies are significant, however, between subarrays and are occasionally as large as 1 second. Consistent sets of anomalies can in general be obtained for all regions except those within  $30^{\circ}$  epicentral distance of NORSAR.
- Time-domain signal traces from various regions show as expected, a general tendency towards lower complexity as the epicentral distance ( $\Delta$ ) increases. Exceptions to this rule are some high complexity signals observed for Kamchatka events ( $\Delta = 65^{\circ}$ ) and Taiwan events ( $\Delta = 80^{\circ}$ ).
- Signal spectral characteristics show strong regional variations, even between regions very close together, and do not always follow the expected tendency towards lower frequencies as the epicentral distance increases. Significant high frequency energy (2 Hz or more) is observed for events from Greece ( $\Delta = 25^{\circ}$ ), Tadzhik ( $\Delta = 40^{\circ}$ ) and the Kurile Islands ( $\Delta = 70^{\circ}$ ).

Signals of dominant low frequency (lower than 1 Hz) are seen mainly from Italy ( $\Delta = 20^\circ$ ), Turkey ( $\Delta = 25^\circ$ ), Kirgiz ( $\Delta = 45^\circ$ ) and Taiwan ( $\Delta = 80^\circ$ ).

- Our limited ensemble of Western Hemisphere events show substantially less high frequency energy than the Eurasian events.
- NORSAR bodywave magnitudes average about 0.2  $m_b$  units lower than either PDE or LASA values, with a standard deviation of 0.3 around this bias. It appears that this negative bias may be explained as signal loss in array beamforming. The PDE-NORSAR  $m_b$  differences appear to be larger at low magnitudes; this is believed to be because PDE in those cases computes an  $m_b$  based upon only a few stations with favorable radiation patterns, thus resulting in  $m_b$  values which are too high.

#### 4. Array Processing Performance

- $\sqrt{N}$  noise rejection is achieved over the entire 0 to 5 Hz band both for subarray and array beamforming. The only exceptions to this rule are occasional strong Rayleigh wave noise fields (3-6 second periods) during storm activity in the North Atlantic Ocean that show coherency at the subarray level. Thus noise rejection totals about 21 dB (8 for subarray and 13 for array beamforming).
- Signal degradation for subarray beamforming is  $1 \text{ dB} \pm 0.5 \text{ dB}$  in the detection frequency band.
- Signal degradation for array beamforming is quite variable, but in the teleseismic zone the following values were found:
  - 3 dB  $\pm$  2 dB for wide band signals
  - 3.5 dB  $\pm$  2 dB in the detection frequency band.



- Diversity-stack beamforming gives the following SNR improvement over the adjusted-delay array beam:  
1.0 dB  $\pm$  0.9 dB for wide band signals  
1.6 dB  $\pm$  1.0 dB in the detection frequency band.
- For detection of Eurasian events, a filter with corner frequencies at about 1.2 and 2.8 Hz and a very sharp rolloff at low frequencies appears to be about optimum. This "standard" filter is similar to the 1.2-3.2 Hz bandpass filter used in the NORSAR on-line Detection Processor.
- Gain in SNR from applying the standard filter is highly variable and shows as expected a strong regional dependence. Average value was found to be 8  $\pm$  4 dB both at the subarray and array beam levels.
- The total net gain of the NORSAR array; i. e., the SNR improvement from the average wide-band single sensor to the adjusted-delay array beam filtered with the standard filter was found to be 25 dB  $\pm$  5 dB.
- The performance of two partial NORSAR arrays, each consisting of eight subarrays, were evaluated by examining SNR losses for 60 Eurasian events relative to the full array. A partial array consisting of the A and b rings gave an average loss of 4.7 dB SNR, while a partial array situated in the Northeast corner of NORSAR averaged a loss of only 2 dB.

## 5. Event Detection Capabilities

Event detection thresholds were estimated on the basis of 452 processed events from 1971 and 1972 that had been reported by sources independent of NORSAR. A maximum-likelihood method was utilized in the estimation procedure. The following results were obtained:

- 90 percent incremental  $m_b$  detection threshold for all of Eurasia combined is approximately 4.2. This conforms well to the corresponding level of 3.9 for LASA reported by Dean et al., (1971), considering that the NORSAR noise level in the detection band is about a factor of 2 higher (0.3  $m_b$  units).
- For the Kuriles-Kamchatka arc (epicentral distance 60-70 degrees) the 90 percent threshold is slightly below 4.3. The average value for the remainder of Eurasia (distances generally 20-55 degrees) is around 4.0.
- The winter 90 percent threshold appears to be slightly higher (0.1  $m_b$  units) than the summer level. This difference is attributed to seasonal variations in the seismic noise level.
- A theoretical estimate of the NORSAR detection threshold based upon seismic noise levels and measured processing losses gives results consistent with the direct method.
- The operational event reporting performance of the NORSAR system was found to be well below array capability in early 1972, especially for near regional events. A significant improvement was observed one year later for the Japan-Kuriles region, where the array then appeared to be operating at close to optimum capacity.

#### 6. Short Period Discrimination

Five standard short period discriminants were applied to a total of 414 events, including 31 presumed explosions, 27 of which were from Eurasia. The main results are as follows:

- Our SP discriminants do not appear to work well for events from the Western Hemisphere.

- Discriminants based on spectral energy distribution seem to be superior to discriminants based upon the complexity of the signal waveform.
- No single discriminant is able to separate completely between presumed explosions and earthquakes. The best separation is obtained by considering the spectral ratio of energy in the bands 1.5 - 5.0 Hz and 0 - 0.55 Hz, although this ratio may be biased because of the high SNR values for all of the presumed explosion events.
- A combination of SP criteria yields some improvement in separation, but no substantial change. The best improvement is obtained by combining one complexity discriminant with one spectral discriminant.
- A preliminary study of the performance of short period discriminants versus that of  $M_s - m_b$  and other SP-LP criteria gives the expected result that the latter ones in general produce a better separation between earthquakes and presumed explosions.

C. Special Report No. 13: Evaluation of the Discrimination Capability of the Norwegian Seismic Array.

This report presents the results of an evaluation of the capability of the short and long period Norwegian Seismic Array (NORSAR) to discriminate between Eurasian earthquakes and presumed explosions. It complements the analyses of the individual performance of various discriminants presented in Special Report No. 11, discussed in the previous subsection, and Special Report No. 12, discussed in Section III, for the NORSAR short and long period arrays, respectively.

The results presented in this report are based upon Eurasian earthquakes occurring between 30 April, 1971 and 31 July, 1972 and Eurasian presumed explosions from 1971, 1972, and 1973. Essentially, the data base consists of events that were processed for both the short period and long period evaluations in Special Reports No. 11 and 12. However, a few additional presumed explosions from 1972 and 1973 have been analyzed in order to increase the common event population. Total number of events is 257, 24 of which are presumed explosions. All of the earthquakes are either shallow or of unknown depth.

A total of nine discriminants have been evaluated in this report. Five of these are based on short period data only; the remaining four combine short and long period information. The discriminants are briefly described as follows:

1. P30 Mean Square

This discriminant, which is a measure of event complexity, is computed by crosscorrelating 4 seconds of the waveform (beginning a few points before P-wave onset) with the next 30 seconds of the waveform and with the noise preceding the signal. A mean square, weighted by the lag, is then computed from the correlations over both 30 seconds of the noise and 30 seconds of the signal. The noise mean square is subtracted from the signal mean square to obtain the discriminant used (Texas Instruments Incorporated, 1971).

2. Autocorrelation Mean Square

This discriminant is also a measure of complexity. The autocorrelations of a 30-second noise gate and of a 30-second signal gate are computed and a weighted mean square then derived from these calculations for the noise and signal. The discriminant is derived from the signal mean square minus the noise mean.

### 3. Envelope Difference

This discriminant is also derived from the P30 correlation by computing the mean-square difference between the envelope correlation and a fixed decaying exponential, the decay rate of which is the average rate for an ensemble of 16 explosions recorded at LASA. As with the first two statistics, envelope difference is a measure of complexity.

### 4. Dominant Period

This discriminant is computed by finding the cycle in the waveform with the maximum absolute amplitude; the dominant period is the duration of this cycle in seconds. This parameter can be estimated with some confidence, even for events with a relatively low signal-to-noise ratio. The dominant period discriminant is a round measure of spectral energy distribution.

### 5. Spectral Ratio

This discriminant is derived from the signal power spectrum over a gate beginning just before the signal arrival. The power spectrum is smoothed over three frequency points, and the power in three bands is computed; Band 1: 0 - 0.55 Hz; Band 2: 0.55 - 1.5 Hz; Band 3: 1.5 - 5.0 Hz. These bands have been selected based on NORSAR data. Spectral ratios computed were Band 3 to Band 2 and Band 3 to Band 1, respectively.

### 6. $M_s$ (Rayleigh) - $m_b$ Discriminant

This discriminant compares the magnitude of the Rayleigh wave signal measured at NORSAR to the reported bodywave magnitude of each event. The detailed procedure of measuring  $M_s$  is described in Special Report No. 12.

### 7. $M_s$ (Love) - $m_b$ Discriminant

This discriminant compares the magnitude of the Love wave signal measured at NORSAR to the reported bodywave magnitude of each event.

#### 8. $AR/m_b$ Discriminant

The AR value is a measure of the Rayleigh wave energy of an event (Brune, Expinosa and Oliver, 1963 ; Evernden, 1969). Our AR values have been normalized to a bodywave magnitude of 5.0 as described in Special Report No. 12.

#### 9. $AL/m_b$ Discriminant

The AL values are computed by the same method as described for AR, except that in this case, measurements are taken of the Love wave energy.

All the nine discriminants defined above are two-dimensional in the sense that discriminant values are plotted against bodywave magnitudes ( $m_b$ ) in order to obtain a good separation between earthquakes and presumed explosions. It is thus important to obtain an  $m_b$  estimate which is as reliable as possible for each event. We have chosen to use the  $m_b$  value quoted in the source bulletin (P, ISM, LASA, NORSAR) in almost all cases, the only exception is events for which the PDE  $m_b$  has been based upon near-field stations only. In those cases, we have used the NORSAR  $m_b$  values. Bodywave magnitudes for the events in the data base ranged from 5.6 to 2.7 for the earthquakes and from 6.3 to 4.4 for the presumed explosions.

The first five discriminants defined above were applied to all events with SP detections at NORSAR; similarly, the last four were evaluated for all LP detections. About 90 percent of all reference events were detected on SP data, while about 70 percent had LP detections (Rayleigh waves, Love waves or both). The NORSAR LP detection capability is actually somewhat lower than these numbers indicate, since "mixed" events (i.e., events for which the LP signals have been buried in signals from a stronger event) were not included in our data base. It was found in Special Report No. 12 that about 20 percent of the events originally selected for that report were of this type.

The major results from this study can be summarized as follows:

- All of the 24 presumed explosions and approximately 90 percent of the earthquakes in the data base were detected on NORSAR Short Period data.
- Twenty of the 24 presumed explosions and approximately 70 percent of the earthquakes in the data base were detected on NORSAR Long Period data.
- Rayleigh waves were detected more often than Love waves for the presumed explosions (20 detections as compared to 14). For the earthquake population, the detectability of Rayleigh waves was only slightly better than that of Love waves.
- Each of the four combined SP-LP discriminants produced close to complete separation for our event set. The  $M_s(\text{Love}) - m_b$  discriminant appeared to give more distinct separation than  $M_s(\text{Rayleigh}) - m_b$ , although the latter one could be applied to more events. The  $AR/m_b$  and  $AL/m_b$  discriminants performed about equally well on the common event set.
- Of the short period discriminants, complexity criteria worked slightly better than the spectral ones. However, it appeared that the spectral discriminants performed relatively better for close-in presumed explosions.
- The combined SP-LP discriminants were not able to give positive identification for events of  $m_b = 5.0$  and lower, since surface waves could not in general be detected at NORSAR for presumed explosions in this magnitude range. However, if "negative evidence" (i.e., the absence of detectable surface waves) was accepted as a way to identify a presumed explosion,

the NORSAR SP-LP discriminants appeared to be effective down to approximately  $m_b = 4.5$  because surface waves were detected for virtually all Eurasian earthquakes above this magnitude.

- The short period discriminants worked relatively well for events of  $m_b$  close to 5.0. However, based on our limited presumed explosion data, indications were that our SP discriminants could not be expected to operate well at  $m_b$  significantly below 5.0 at teleseismic distances.
- Correlation was high between discriminants within each of the three subclasses (combined SP-LP, SP complexity, SP spectral content). However, the combined SP-LP criteria were only slightly correlated with the SP discriminants, thus indicating that some improvement may result from multivariate criteria.
- Detailed analysis of some "difficult" events indicated that there were cases where SP discriminants worked better than one of the four combined SP-LP criteria. However, in view of the high false alarm rate (close to 10 percent) for our SP discriminants, it appears that decisions (earthquake versus presumed explosion) based on SP information alone will generally have a substantial probability of error. The main benefit of the standard SP discriminants thus appears to be to provide corroborative evidence to the SP-LP criteria.
- Since all the discriminants studied in this report are  $m_b$  dependent, it is essential to have a precise estimate of this parameter. It appeared that in some cases where we misclassified an earthquake the main problem was an unreliable  $m_b$  estimate.



It is important to remember that these conclusions are based on the performance of a single array at teleseismic distances; they are not necessarily applicable to network discrimination performance or to first-zone ( $\Delta < 15^\circ$ ) discrimination capability.

## SECTION V

### VLPE STATION EVALUATION AND NETWORK EVALUATION TASKS

The results of the VLPE station evaluation task and the network analysis task are presented in five reports. Both tasks are combined in this section because the two main reports, Special Report No. 6 and Special Report No. 14, discuss both tasks together. Special Reports No. 3 and No. 10 discuss ambient noise characteristics at the individual stations. Special Report No. 4 discusses a statistical model for estimating long-period Rayleigh wave signal persistence for a seismic network. Summaries of these reports are given below.

- A. Special Report No. 6: Evaluation of the Detection and Discrimination Capability of the Very Long Period Experiment (VLPE) Single Stations, VLPE Network, and the VLPE-ALPA-NORSAR Combined Network.

This report presents an evaluation of the detection and discrimination capabilities of the Very Long Period Experiment (VLPE) single stations, the VLPE network, and the VLPE-ALPA-NORSAR combined network. The purpose of the VLPE is to improve detection and discrimination capabilities with the use of a small network of high gain, high quality, long period digital seismographs at various locations throughout the world.

The VLPE instrumentation has been described in detail by Pomeroy, et al.(1969), and studies of the data from the station at Ogdensburg, New Jersey have been presented by Savino, et al.(1971). A general review of eight of the long period stations with their capabilities and the application of various filter techniques to the digitally recorded data have also been given by

Savino, et al. (1972). The results of a preliminary evaluation of the VLPE station network have been presented in two reports by Texas Instruments Incorporated, (Benno, 1972; Harley, 1972). They presented discussions of the vertical and horizontal noise spectra and the theoretical capability of detection, respectively. Their conclusions were limited by the small quantity of observational data available at that time.

The data base for this report consists of the analysis of 548 events of 2130 event-station pairs. The results of techniques applied to this data base included the following:

- A description of Rayleigh waves as a function of magnitude ( $m_b$ ) and distance ( $\Delta$ ) for a large ensemble of Eurasian events at (1) all available single VLPE sites, (2) the VLPE stations as a network, and (3) the VLPE-ALPA-NORSAR networks combined.
- The relationship of  $M_s$  at 20 seconds to  $m_b$  for VLPE single sites, the VLPE network and the VLPE-ALPA-NORSAR combined network
- The relationship of  $M_s$  at 20 seconds and at 30 seconds to  $M_s$  at 20 seconds for VLPE stations.

This large data base covers two periods: January 1 - March 20 and June 1 - July 31 of 1972.

The capability to discriminate between presumed explosions and earthquakes using VLPE data is also discussed. Presumed explosion data are added to the  $M_s$  at 20 second period versus  $m_b$  data from the VLPE stations presented earlier. Finally, the Love to Rayleigh wave amplitude ( $LQ/LR$ ) ratio is presented for the VLPE single stations and the VLPE network.

We can summarize the results from this study of the VLPE network as follows:

- A measure of the reliability of a network is the amount of data that is available and usable. We show that less than 50% of the expected data from the VLPE network were available and usable.
- Detection capability based on the presence of Love waves was not measured because of erratic static gains that were frequently encountered on the horizontal components at virtually all VLPE sites.
- The 90% detection level for Rayleigh waves at single VLPE stations ranges from an  $m_b$  of 4.6 to 4.9 at  $\Delta \leq 50^\circ$  and an  $m_b$  of 4.8 to 5.0 at  $\Delta > 50^\circ$  for the winter event ensemble. The detection level for the summer event ensemble ranges from an  $m_b$  of 4.4 to 4.5 for  $\Delta \leq 50^\circ$  and an  $m_b$  of 4.5 to 4.9 for  $\Delta > 50^\circ$ .
- The 0.2, 0.3, and 0.4 magnitude differences in the winter and summer detection levels at TLO, KON, and OGD respectively, agree with differences in the noise levels for corresponding time periods.
- The VLPE network has a 90% detection level as good as the best single VLPE station; that is, an  $m_b$  of about 4.8 at either KON or CHG for the winter events at all distances and an  $m_b$  of about 4.6 at either KON or OGD for the summer events at all distances.
- Two or more VLPE stations should have been operational at distances less than  $50^\circ$  for all events. However, only about one station was operational and less than 50% of the VLPE stations were operational at all distances. The 90% network detection level showed little or no improvement at  $\Delta \leq 50^\circ$  over that for  $\Delta > 50^\circ$  for all events. Therefore, had most of the

stations been operational in both distance ranges, we would have expected the VLPE network detection level to improve significantly relative to the best single station.

- When the ALPA and NORSAR networks are combined with the VLPE network, the 90% detection level decreases (relative to the VLPE network alone) about 0.2 units of magnitude for both the winter and summer events.
- The variance of the least squares linear fit for all  $M_s - m_b$  data is significantly greater for the winter period than for the summer period. This is mainly due to the increased noise level during the winter period, but also may be due, in part, to erratic gains at some of the stations.
- Single station discrimination between earthquakes and explosions may be possible at selected sites on the basis of the data presented.
- The discrimination level for the VLPE network is about  $M_s = 4.1$  and  $M_s = 3.6$  for the winter and summer months, respectively.
- The discrimination level for the VLPE-ALPA-NORSAR combined networks is about  $M_s = 3.6$  and  $M_s = 3.2$  for the winter and summer months, respectively.
- The network discrimination levels stated in the previous two paragraphs are conservative estimates. These estimates are based on the 90% detection level ( $m_b$ ) and Tsai's (1972) theoretical  $M_s - m_b$  curve for earthquakes.
- Several earthquakes located at about  $30^\circ$  N latitude and  $50^\circ$  to  $80^\circ$  E longitude are consistently misclassified.

- The relationships for  $M_s$  determined at 40 seconds period and at 30 seconds period relative to  $M_s$  at 20 seconds period are as follows:

$$M_s(40) = M_s(20) - (0.62 \text{ to } 0.70)$$

$$M_s(30) = M_s(20) - (0.29 \text{ to } 0.33)$$

The  $M_s(30):M_s(20)$  relationship agrees with that of Marshall and Basham (1972) for continental Eurasian paths. However,  $M_s(40):M_s(20)$  does not agree with their results.

- The mean Love to Rayleigh wave amplitude ratio,  $LQ/LR$ , of 1.20 determined for the VLPE network, is consistent with those of 1.16 and 1.35 independently determined at ALPA and NORSAR. The detection rate of Love and Rayleigh waves is nearly equal at both ALPA and NORSAR. However, we were unable to determine the detection rate of Love waves for the VLPE network.

B. Special Report No. 14: Evaluation of the Noise Characteristics and the Detection and Discrimination Capabilities of the Very Long Period Experiment (VLPE) Single Stations and the VLPE Network.

This report presents an evaluation of the noise characteristics of the Very Long Period Experiment (VLPE) single stations and the detection network. The purpose of the VLPE is to improve detection and discrimination capabilities with the use of a small network of high gain, high quality, long-period digital seismographs at various locations throughout the world.

Special Reports No. 3 and No. 10, discussed in the next two subsections, describe the vertical and three component structure of earth noise for eight VLPE stations. Special Report No. 6 presented the preliminary detection and discrimination capabilities of nine VLPE stations, the VLPE network, and the VLPE-ALPA-NORSAR combined network.

The data base for this report extends the study of vertical and horizontal earth noise with the VLPE data during November and December 1972, and January 1973. The data base for the signal analysis is extended and consists of 874 Eurasian events for a total of 3577 event-station combinations. The results of techniques applied to these data include the following:

- An analysis of the long-term broadband vertical earth noise, maximum trace amplitude versus RMS amplitude, three component broadband earth noise, and intercomponent noise correlation.
- Maximum-likelihood estimates of detection capability based on  $m_b$  for VLPE single stations and the VLPE network.
- The estimated reduction of mixed events in terms of probabilities for various VLPE networks based on the present VLPE capability.
- Preliminary analysis of the matched filters and the three component adaptive filter on a restricted suite of events.
- Discrimination capability of single VLPE stations and the VLPE network as functions of  $M_s$  versus  $m_b$ , Love to Rayleigh wave amplitude ratios, and surface wave radiation patterns.

Data from vertical and simultaneous component noise samples from VLPE sites show the following:

- The presence of a "stable noise minimum" is evident in the period range of approximately 22-35 seconds.
- At most VLPE sites a microseismic peak is present in the 17-20 second period range.

- There is a leveling off of the vertical and horizontal noise field at periods below the microseismic peak while at periods above 30-35 seconds there is great variability in the horizontal noise field relative to the vertical noise field.
- Seasonal variations in the vertical noise fields are suggested by the slowly changing long term nature of the vertical noise fields.
- Intercomponent frequency-dependent cross-correlation of the RMS amplitudes is rarely observed but when present occurs only at the same periods on both correlated components. We interpret this negative result to mean that in general noise on one component is independent of noise on the other two.

A larger more continuous data base is required to ascertain whether seasonal variations in the noise field occur at the VLPE sites. We have insufficient noise data for stations EIL, ZLP, and MAT for all aspects of noise analysis.

The conclusions as to the detection capability of the VLPE stations are:

- The difference in the 50 percent detectability level between all events closer than 50 degrees epicentral distance and all events further than 50 degrees ranges from 0.2 to 0.5  $m_b$  units.
- The 50 percent detection levels of the best stations, CHG and KON, are at  $m_b$  of 4.35 and 4.38, respectively while the average 50 percent level for all stations is at an  $m_b$  of 4.56.
- The three networks requiring one operational station are almost equivalent in terms of the 50 percent  $m_b$  threshold



( $m_b \simeq 4.2$ ). The same three networks requiring two operational stations also are about equivalent in terms of the 50 percent  $m_b$  threshold ( $m_b \simeq 4.5$ ).

- $M_s$  threshold values are subject to significant uncertainties, and it is expected that more reliable estimates may be obtained in our future studies when direct detection statistics based on  $M_s$  values become available.
- Based on 844 events with at least one operational station we classified 22 percent of the events as mixed events.
- The number of events that were mixed at all network stations was 49 (for an average of 3.8 operational stations); this is 5.8 percent of the 844-event ensemble.
- Matched filters (reference waveform and chirp) yield an average of 3.6 dB signal-to-noise ratio improvement when applied to Rayleigh waves.
- Application of matched filters increases the number of detections by a factor of two. However, the small data base used precludes the determination of accurate detection thresholds.
- Preliminary evaluation of the three component adaptive filter yields detection results comparable to those for the chirp filter.

The VLPE station discrimination capability may be summarized as follows:

- $M_s$  versus  $m_b$  separation between earthquakes and presumed explosions is not distinct at single VLPE stations or the total

VLPE network. We need to study regional and temporal subsets of the data and various networks of VLPE sites to define the problems of discriminating with  $M_s$  and  $m_b$ .

- Single station and total-network linear trends of  $M_s$  versus  $m_b$  are determined. However, the effect of noise on low magnitude estimates must be considered and trends must be segmented or fitted with a higher order polynomial to ascertain the true station and network response to events from Eurasia.
- We obtained a mean of 1.18 for the Love to Rayleigh wave amplitude ratio for Eurasian earthquakes, and for two presumed explosions from eastern Kazakh, three ratios gave an average LQ/ LR of 0.72.
- A mean LQ/ LR of about 0.60 was determined from 412 ratios reported by von Seggern (1972) for explosions which were mostly from the NTS with a few from Amchitka. This compares favorably with the eastern Kazakh value of 0.72, especially since this value is probably high due to the almost total lack of Love wave amplitude measurements for any of the presumed explosions.
- No correlation of LQ/ LR ratios between regions and stations having the same azimuths is observed. This suggests that either the earthquake source parameters vary significantly within the defined regions and/or that the data available from the VLPE horizontal components are of poor quality.
- Attempts to determine radiation patterns for presumed eastern Kazakh explosions and earthquakes near the presumed explosions were unsuccessful due to the lack of LR or LQ data at many azimuths.

For future studies, we make the following recommendations:

- A larger more continuous data base is required to ascertain whether seasonal variations in the noise field occur at the VLPE sites. Acquire more data for stations EIL, ZLP, and MAT to complete the noise analysis at these sites.
- Determine the detection thresholds of VLPE stations and networks in terms of  $M_s$  based on direct detections by stations when sufficient  $M_s$  data becomes available.
- Enlarge the data base of results from matched filters and the three component filter to define the capabilities of these techniques.
- Determine the true  $M_s$  versus  $m_b$  response of the single stations and the network for Eurasian events.

C. Special Report No. 3: Long-Term Broad-Band Vertical Earth Noise Structure at Very Long Period Experiment Sites.

Several recent reports (Pomeroy, et al. 1969; Murphy, et al. 1972) have identified the presence of a 'stable noise minimum' in the structure of the earth's seismic noise field. This feature has been interpreted in terms of non-propagating motion related to barometric fluctuations acting on the surface of the earth (Capon, 1969; Sorrells and Der, 1970; Sorrells, et al. 1971; Savino and Rynn, 1972) rather than the residual motion of signals initiated by earthquakes or explosions. The presence of the minimum, which usually lies in a band of wave periods of about 30 to 40 seconds, has been demonstrated on the basis of a few samples of 'typical' seismic noise recordings a few hours in length. Since noise minimum offers the possibility of lower amplitude signal detection capability for long period surface waves which might be obscured in higher microseismic amplitudes in the 15 to 18 second band, it has assumed importance in seismic discrimination problems.

The intent of this report is to extend the observational base for delineating the stable minimum at several locations throughout the world in terms of amplitude and bandwidth. We also will show some other important characteristics of earth noise structure in the 13.5 - 62.5 second band which are of some potential interest in signal detection problems and to an understanding of earth noise structure in general.

The results show that the presence of a 'stable noise minimum' at long periods in the seismic noise field structure is clearly evident at the seven VLPE locations studied. The bandwidth of the minimum is somewhat more location dependent than suggested by earlier reports about its character, with bands ranging from 25-50 second periods at the widest to 21-30 second periods at the narrowest and using 3 dB above minimum RMS amplitude to delineate the bandwidth. Stability of the minimums is indicated by low variability of the RMS amplitudes in the bandwidths compared to shorter or longer period motions.

Lowest RMS amplitudes averaged over a minimum of 33 hours of observations range from 2.1  $m\mu$  to 3.6  $m\mu$ , and maximums for the same data samples range from 8.4 to 18.2 millimicrons. There appears to be a general minimum level of RMS ground noise at all locations which may be seasonally dependent, and which essentially defines a "floor" in the noise structure over long periods of time. The floor appears to be related more to energy with periods included in the band of the stable minimum than in other more variable parts of the spectrum.

A psuedo-stable minimum is suggested at periods between microseismic peaks at 6-8 second and 17-19 second wave periods. Observed average RMS amplitudes tend to level off or decrease at periods shorter than 17-19 seconds in the data presented here, and there is a corresponding decrease in variability of the ground motions. This decrease is probably seasonal in nature, but may also be a characteristic of the location itself since:

the decrease is evident at several locations over time periods as long as about 90 days.

The RMS amplitude observations approximate a lognormal distribution, and the distribution of logarithms of RMS amplitude is relatively constant over the bandwidth. Amplitude changes over the bandwidth show very little linear correlation for either RMS amplitudes or log amplitude comparisons, reflecting the independence of the noise minimums from the stronger microseismic activity peak.

Characteristics of the earth noise structure demonstrated here provide some additional confidence in the stability of the noise minimum identified earlier in the vertical field and show the presence of another relative minimum in the bandwidth. Future work to describe the structure of the horizontal noise field is underway, and additional observations of the vertical noise field at both the locations described in this report and at new locations are intended.

D. Special Report No. 10: Simultaneous Three-Component Broad-Band Earth Noise Structure at Very Long Period Experiment Stations.

Vertical earth noise structure at Very Long Period Experiment sites was reported by Alsup and Becker (1973) for over 600 hours of noise sampling. This report extends the noise analysis to the horizontal earth noise field for the VLPE installations during 1971 and early 1972. Very few estimates of the horizontal field have been published and few long-term simultaneous three-component observations have been presented.

Results of the analysis are given in terms of simultaneous one-hour samples of the noise field on three-component recording systems which sense motion in vertical, North-South, and East-West planes at each location. Power Spectral Density (PSD) estimates in 16 narrow bands (4 millihertz bandwidths) were converted to RMS ground motion across the total bandwidth (about

13.5 - 62.5 seconds (equivalent period) by applying system response correction at the center frequency of each narrowband. Less data are reported here than for the vertical noise study alone because operational status for all three components was required to maintain simultaneous sampling throughout. Data presented here are also essentially free of known seismic signals from earthquakes or explosions.

Data from the simultaneous three-component noise samples taken at VLPE sites shows that the long-term characteristic of the horizontal noise field structure approximates that of the vertical field. The bandwidth of the widely observed "noise window" usually lies in the 22-35 second period range in the horizontal field rather than 25-40 seconds (or broader) seen in the vertical field. Wide horizontal bandwidths for the minimum approximating the vertical field are present at some sites (Kongsberg, Ogdensburg), but a tendency for a more rapid increase in horizontal noise toward longer periods is evident (perhaps caused by earth tilt rather than horizontal motion). Average earth noise levels are observed to be higher on the horizontal channels as compared to the vertical channel with a few exceptions.

Variability of the horizontal noise field also follows the patterns of the vertical field, with low variability in the noise minimum (reflecting stability of the low levels) and indications of low variability at wave periods less than 16-17 seconds (a pseudo-stable minimum trend). Greatest variability in the horizontal field is also observed near the microseismic peak at 17-20 seconds period and at wave periods greater than 35-40 seconds. The distribution of RMS noise amplitudes approximates lognormality, as opposed to normality, across the 13.5 - 62.5 second band.

Intercomponent frequency-dependent cross correlation of the RMS amplitude (or log amplitude) changes typically show weak to moderate correlation only at the same wave periods on both components when such

correlation is present at all. Essential lack of correlation (less than .69) is common over much of the bandwidth at most sites. Strong correlation ( $\rho = .90$  or greater) is not common, and where it is present, the bandwidth of correlation is very limited.

Since the noise samples are one hour in length, the lack of correlation cannot be interpreted to mean that the components do not react to a propagating wave arriving at the instrument location or that no correlation within each sample exists. The observation can be made, however, that time and frequency dependent changes in noise power over the long term are not strongly correlated at most locations, and noise on one component may be independent of noise levels on the other two. Similarly noise levels in one part of the bandwidth on any particular channel appear to be independent of noise levels in other parts of the band, and a single component may have low noise when the other two are in a high noise field. Data treatments to improve signal detectability must therefore be designed on the characteristics of each channel, and signal detectability on each data channel can be an independent function of time in terms of the noise field structure.

E. Special Report No. 4: A Random Model for Half-Amplitude Decay Times of Rayleigh Waves.

Estimation of the significance of seismic signal interference in the operations of a network of seismic recording stations is of importance both toward understanding signal detection potentials and for evaluating the necessity of development and use of "anti-interference" analytical tools. Use of the seismograms from the Very Long Period Experiment (VLPE) stations provides the opportunity for study of generalized multiple path signal trends in a network sense. Current seismological trends are toward centralization of operations to the point where world-wide station distributions are treated simply as instrument arrays, and the kind of approach taken here is both necessary and vital to successful use of data provided by the recording stations.

While most who are familiar with seismograms can call to mind some approximate length of time that long-period Rayleigh waves are visible on our recordings, virtually no numerical data on the subject have been published, and no time-amplitude persistence reports are known to us. The subject is of interest upon occasion, particularly if we wish to have a measure of some specific signal at a time when another signal occupies the seismogram. The length of time that some level of amplitude of the "unwanted" signal persists is also of some interest if we wish to forecast the possibility that the signal interference is at a level where the required measurement will be obscured. We hope to provide a method for estimation of the time-amplitude characteristics of long-period Rayleigh wave signals with this study, using signals recorded by the VLPE stations from Eurasian earthquakes as a data base.

Demonstration of randomness of Rayleigh wave half-amplitude decay times, within constraints of wide spatial distribution of sources and recording stations (and at least a moderate range of source magnitudes), provides a basis for predicting signal amplitude - time relationships on seismograms. The two parameter gamma probability distribution describes the half-amplitude occurrence times adequately in a statistical sense. The parameter  $\lambda$ , which requires determination to use the distribution, can be directly derived from a set of observations of the half-amplitude times in recorded signals.

Practical use of the result given here lies in estimation of signal interference times expected in a network of recording stations during some typical period of operating time. Using the observed number of sources occurring (or expected) during such a period, distribution of the sources in terms of magnitude, and an acceptable amplitude-distance-magnitude relationship, the peak signal amplitudes can be estimated. Given these amplitudes, the time



rate of amplitude decay by half-amplitude increments can be expressed at pre-selected probability levels.

A further continuation of the work includes an evaluation of the multiple source - single station signal amplitude decay times. If the randomness observed here is primarily a function of multiple paths and varying source magnitude, randomness of the Poisson type should also be found in the single station recordings with a sufficiently large base of observational data. The effects of the distance distribution of active seismic regions relative to the single stations can then be accounted for, and a more accurate estimate of potential interference times by Rayleigh waves in the network will result.

## SECTION VI

### RESEARCH TASK

The research task consisted of the evaluation of two signal processing algorithms: the three component adaptive filter developed at Lamont-Doherty Geological Observatory for long-period surface waves and the Fisher detector, also known as the similarity detector. The evaluation of the adaptive filter is discussed in Special Report No. 15 and the evaluation of the Fisher detector is discussed in Special Report No. 16. Summaries of their results are presented below.

#### A. Special Report No. 15: Evaluation of an Adaptive Three Component Filter.

The adaptive filter studied here was developed at the Lamont Geophysical Observatory (Shimshoni and Smith, 1964) and is a three component processor designed to improve the detectability of long-period Rayleigh and Love waves. It takes advantage of the fact that when Rayleigh and Love waves are present there is a known phase relationship on the three mutually perpendicular long period seismometer traces. Potentially, improvements in signal-to-noise ratio can be achieved when these phase relationships are utilized in the filter design.

This report presents results of an evaluation of the adaptive filter using both synthetic and real data. Synthetic data included known signals buried in noise at various signal-to-noise ratios which were used to study the signal-to-noise improvement characteristics of the filter; random noise was used to study its false alarm characteristics. Real data included single site and beam data from the Alaskan Long Period Array (ALPA) and single stations from the Very Long Period Experiment (VLPE) network.

The following conclusions are based on a comparison of the performance of the adaptive filter with a simple bandpass filter on single site and beam data from ALPA, data from the VLPE network, and on synthetic data.

The adaptive filter output can have as much as 8 dB improvement in signal-to-noise ratio over the bandpass filter output, for both single site and beam data. However, gain is achieved on beam records only when signals are already detected on bandpass filter outputs. Thus no gain in detections results from application of the filter to beam data. This behavior can be understood from the intercomponent correlation of the noise introduced by beamforming. No change in detectability was observed when the adaptive filter was applied before instead of after beamforming.

Gain in signal-to-noise ratio on single site data takes place even when the signal was not detected on bandpassed records. Thus an increase in detections is possible. For the sample of events reported as recorded at the VLPE stations, the percent of detections rose from 11% to 37% when the adaptive filter replaced the bandpass filter. The percent of detections at each magnitude was as large as, or larger, when the adaptive filter was used than when only bandpass filtering was used.

The adaptive filter did not reduce the amplitude of misoriented Rayleigh waves much more than the geometrical factor to be expected from incorrect alignment of the axes. However, the Love wave rejection of off-azimuth signals was much greater than that expected from misalignment alone.

The adaptive filter did not create spurious signals from noise. Its false alarm rate thus depends on the ability of the analyst to distinguish propagating noise from seismic signals.

For these reasons it is recommended that the adaptive filter be routinely used to process VLPE data, but that it not be used on beam data.

B. Special Report No. 16: Preliminary Comparison of Automatic Fisher and Conventional Power Detection Algorithms.

This report studies the performance of two seismic signal detectors; the Fisher detector, (Edwards, Benno, and Creasey, 1967) and the beam power detector. These detectors are designed to automatically process seismic data and alert the analyst whenever some criterion is met which indicates the presence of a signal. The Fisher detector responds to similar outputs from the individual array elements, while the power detector responds to sudden changes in the average power level over the array.

This report investigates the response of the detectors to signals of varying signal-to-noise ratio; their performance characteristics in terms of false alarm rate versus detection probability; their response to off-azimuth signals; and their response to irregularities in the data such as glitches, spikes, and amplitude and phase distortion. Both theoretical and experimental results are presented.

A theoretical analysis of the Fisher detector and conventional detector has been carried out, assuming only that the noise is not correlated with itself or the signal. This analysis shows that the Fisher and conventional detectors should respond in the same way to signals and should have the same response to off-azimuth signals. The conventional detector is not sensitive to phase or amplitude distortion, but the Fisher detector output is reduced by phase distortion, although not by amplitude distortion.

Experimental results confirm these predictions. The experimentally determined performance characteristic, an objective measure of how well a detector performs, is the same for the Fisher detector and conventional detector, within the limits imposed by the data sample. The length of time over which the data are averaged has a significant effect. Longer times, up to at least 256 seconds, give better results.

The rejection of off-azimuth signals is the same for the detectors, as predicted. Evidence of a predicted saturation effect due to phase distortion in the Fisher detector was found. The behavior of the detectors in response to glitches in the data was investigated, and the prediction that the Fisher detector does not respond to glitches was confirmed.

One of the difficulties with the conventional beam power detector in the past was that an accurate estimate of the average noise power,  $\sigma_o^2$ , was hard to find. It was anticipated that the Fisher detector would prove superior to the conventional detector because it does not require such an estimate. The lack of distinction between the detectors found in this study implicitly suggests that the method used to estimate  $\sigma_o^2$  is valid.

A number of suggestions for further study can be made. The data base should be expanded, both by investigating more events in the magnitude range of this report, and by taking a wider range of magnitudes. The performance characteristics may be distinguishable if this is done. Other results suggest that even longer time gates than were used here may give somewhat better performance by the Fisher detector.

SECTION VII  
SEISMIC NETWORK SYSTEMS STUDY -  
SPECIAL REPORT NO. 17

Over the thirteen years of the VELA UNIFORM Program substantial progress has been made towards solving the nuclear test detection problem. Improvements in signal detection capabilities, event location accuracies, and identification methods have been significant, as have advances in hardware, software and communications technology. Our fundamental understanding of both the seismic source and the geophysical properties of the earth have improved greatly. These advances have enabled us to formulate a reasonable technical approach to the solution of the overall test detection problem, to define approaches to remaining unsolved or partially solved test detection problems, and to specify quantitatively the limitations inherent in a teleseismic nuclear surveillance system. Thus it becomes timely to proceed to the next research phase, which is to begin a detailed definition and analysis of the seismic surveillance network implementation and operation problem.

This report describes the results of our seismic network systems study which is directed towards the network implementation and operations problem. Overall objectives of the study are:

- For selected seismic surveillance networks to specify in detail implementation requirements (hardware, software, communications, operational and analytical requirements) and operations procedures.
- To identify areas (e.g., automatic processing methods, communications methods) where additional research will be required to fully define implementation techniques.

- To perform cost/performance trade-off studies so that implementation decisions can be made on a quantitative basis.

In short, the objective of this study is to outline the network implementation and operation problem so that quantitative statements concerning design concepts, operating performance, costs and problem areas requiring additional research can be made.

## SECTION VIII

### REFERENCES

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APPENDIX A  
LIST OF REPORTS FROM CONTRACT  
F33657-72-C-0725

A. QUARTERLY REPORTS

1. Quarterly Report No. 1, covering the period 1 April 1972 to 30 June 1972, 15 July 1972.
2. Quarterly Report No. 2, covering the period 1 July 1972 to 30 September 1972, 15 October 1972.
3. Quarterly Report No. 3, covering the period 1 October 1972 to 31 December 1972, 15 January 1973.
4. Quarterly Report No. 4, covering the period 1 January 1973 to 31 March 1973, 15 April 1973.
5. Quarterly Report No. 5, covering the period 1 April 1973 to 30 June 1973, 13 July 1973.
6. Quarterly Report No. 6, covering the period 1 July 1973 to 30 September 1973, 25 October 1973.
7. Quarterly Report No. 7, covering the period 1 October 1973 to 31 December 1973, 15 January 1974.

B. SPECIAL REPORTS

1. Indirect Estimates of Surface Wave Detection Probabilities, by Terence W. Harley and Leo N. Heiting, 1 August 1972.
2. Simulated On-Line Adaptive Processing Results Using Alaska Long Period Array Data, by Thomas E. Barnard, 23 October 1973.

3. Long-Term Broad-Band Vertical Earth Noise Structure at Very Long Period Experiment Sites, by Stephen A. Alsup and Ervin S. Becker, 21 February 1973.
4. A Random Model for Half-Amplitude Decay Times of Rayleigh Waves, by Stephen A. Alsup and David G. Lambert, 25 January 1973.
5. Selection of Reference Waveforms for Matched Filter Processing for Long Period Signals from Seismic Events, by Rudolf Unger, 24 October 1973.
6. Evaluation of the Detection and Discrimination Capabilities of the Very Long Period Experiment (VLPE) Single Stations, VLPE Network, and the VLPE-ALPA-NORSAR Combined Network, by David G. Lambert and Ervin S. Becker, 18 May 1973.
7. Continued Evaluation of the Norwegian Long-Period Array, by Philip R. Laun, Wen-Wu Shen, and William H. Swindell, 2 November 1973.
8. Final Evaluation of the Detection and Discrimination Capability of the Alaskan Long Period Array, by Alan C. Strauss, 29 June 1973.
9. Continued Evaluation of the Norwegian Short-Period Array, by Frode Ringdal and Richard L. Whitelaw, 10 August 1973.
10. Simultaneous Three-Component Broad-Band Earth Noise Structure at Very Long Period Experiment Stations, by Stephen A. Alsup and Ervin S. Becker, 29 June 1973.
11. Final Evaluation of the Norwegian Short-Period Array, by Frode Ringdal and Richard L. Whitelaw, ALEX(01)-STR-73-11, 2 November 1973.

12. Final Evaluation of the Norwegian Long-Period Seismic Array, by Philip R. Laun, Wen-Wu Shen, and William H. Swindell, ALEX(01)-STR-73-12, 3 December 1973.
13. Evaluation of the Discrimination Capability of the Norwegian Seismic Array, by Frode Ringdal, ALEX(01)-STR-73-13, 23 November 1973.
14. Evaluation of the Noise Characteristics and the Detection and Discrimination Capabilities of the Very Long Period Experiment (VLPE) Single Stations and the VLPE Network, by David G. Lambert, Sidney R. Prahl, and Alan C. Strauss, ALEX(01)-STR-73-14, 1 November 1973.
15. Evaluation of an Adaptive Three-Component Filter, by Stephen S. Lane, ALEX(01)-STR-73-15, 30 November 1973.
16. Preliminary Comparison of Automatic Fisher and Conventional Power Detection Algorithms, by Stephen S. Lane, ALEX(01)-STR-73-16, 30 November 1973.
17. Seismic Network Systems Study, by Robert L. Sax and Staff, ALEX(01)-STR-74-01, 31 January 1974.

#### C. FINAL REPORT

1. Final Report, Extended Array Evaluation Program, by Terence W. Harley, ALEX(01)-FR-74-01, 31 January 1974.

#### D. PAPERS PRESENTED

1. Event Detection Capability of the Norwegian Seismic Array (NORSAR), presented by Frode Ringdal at the American Geophysical Union Fall Annual Meeting, 13 December 1973.